

COMPARISON OF FUELS USED FOR CHEMICAL HEATING OF THE WORKING MEDIUM IN GASDYNAMIC HIGH-ENTHALPY FACILITIES

V.V. Shumskii

Institute of Theoretical and Applied Mechanics SB RAS,
630090 Novosibirsk, Russia

In doing gasdynamic research on a model with burning, it is required, as a rule, to reproduce full-scale stagnation pressures and temperatures with acceptable model dimensions and flow durations [1,2]. At moderate hypersonic Mach number $M_{in} = 7-8$, the working-body parameters required for such studies may be easily obtained in a high-enthalpy short-duration facility. Obtaining higher or lower values of M_{in} requires (although for different reasons) higher power consumption. Previously [2], we have considered some methods for obtaining full-scale approach-flow parameters, up to $M_{in} = 11-12$, that use various combinations of heating means: in the external source, chemical or electrical heating in a plenum chamber, and adiabatic after-compression. In [1], it has been shown that chemical heating, in principle, allows one to successfully solve the problems related to increasing the consumed power in a scheme with a double plenum chamber with decreasing M_{in} down to 3.5–4 if additional electric heating is provided. However, in [1] we ignored all limitations imposed by ignition ranges of chemical substances used for heating the working body.

In the present study, we compare hydrogen, acetylene, propane and their mixtures with nitrogenous oxide from the viewpoint of the amount of fuel required for reproducing full-scale enthalpy and pressures, with due regard made for their ignition conditions.

We consider the range of Mach numbers $M_{in} = 4-7$ and the scheme of a facility with a double plenum chamber, Fig. 1. The working body heated by a chemical reaction in the first plenum chamber (1) is throttled to a pressure $p_{ch2} = p_{0in}$, where p_{0in} is the stagnation pressure for a flight with a Mach number M_{in} at a height H , and p_{ch2} is the pressure in the second plenum chamber (2). This scheme ensures a certain pressure in the first plenum chamber that does not depend on the output pressure; it therefore makes it possible to substantially prolong the flow duration due to the condition $p_{ch1} \gg p_{0in}$.

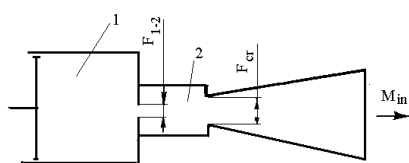


Fig. 1. Schematic of the experimental facility.

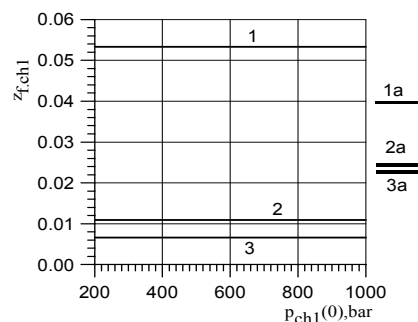


Fig. 2. Molar fractions of the fuel injected into the first plenum chamber. $M_{in} = 4$; $H = 20$ km.

1— H_2 ; 2— C_2H_2 ; 3— C_3H_8 ; 1a, 2a, and 3a – lower end points of the ignition range for H_2 , C_2H_2 , and C_3H_8 .

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Three-component mixture. Into the first plenum chamber, a mixture is injected which consists of a fuel, air, and compensating oxygen. As the fuel, we consider either hydrogen H_2 , acetylene C_2H_2 or propane C_3H_8 . Oxygen is added into the initial mixture in such amounts that to compensate for the atmospheric oxygen burned out in the chemical reaction and to ensure a mass concentration of oxygen among reaction products equal to that in air, 0.231. After the chemical reaction held in the regime $v=\text{const}$, the working body in the first plenum chamber will consist of reaction products of the three-component mixture plus non-burnt part of the fuel. In the present calculations, we assume the completeness of fuel combustion to equal 0.95.

Figure 2 shows the molar fractions $z_{f,chl}$ of the fuel, pumped into the first plenum chamber, that is required for reproduction of the working-body entropy the as the body approaches the model. It is seen from Fig. 2 that the molar fractions of the fuel do not depend on the pressure in the first plenum chamber. The latter may be explained by the fact that for all p_{chl} the relation $h_{chl} = h_{0in}$ should be valid, where h_{chl} and h_{0in} are the specific physical enthalpy of the working body in the first plenum chamber and that in the approach flow. Depending on p_{chl} , the amount of the fuel varies, but the mass fraction required for ensuring the condition $M_{in} = \text{const}$ remains unchanged.

Figure 2 depicts curves 1a, 2a, and 3a that indicate the lean forced-ignition limits for hydrogen, acetylene, and propane in air, respectively: 0.04, 0.025, and 0.0237 [3]. It is clearly seen that at $M_{in} = 4$ only hydrogen is capable of ensuring fuel ignition in the three-component mixture. The fractions of acetylene and propane required for the working body to be heated from the temperature at which the initial mixture is injected into the first plenum chamber, 300 K, to $h_{chl} = h_{0in}$ are well below their ignition limits. Therefore, acetylene- or propane-containing three-component mixtures cannot be used for reproducing the full-scale entropy at $M_{in} = 4$. These fuels may be used if the condition $h_{chl} > h_{0in}$ is admissible, i.e., if the stagnation temperature of the working body as this body approaches the model may exceed the full-scale stagnation temperature T_{0in} . Figure 3 shows the same data versus the modeled M_{in} number for a trajectory with a velocity head of 0.6 bar. It is seen from Figure 3 that, judging from the fuel-air mixture ignition condition, the use of acetylene as a heating source is possible from $M_{in} \sim 5.7$ on, whereas that of propane from $M_{in} \sim 6.9$ on. If, in solving a particular problem, the working-body enthalpy

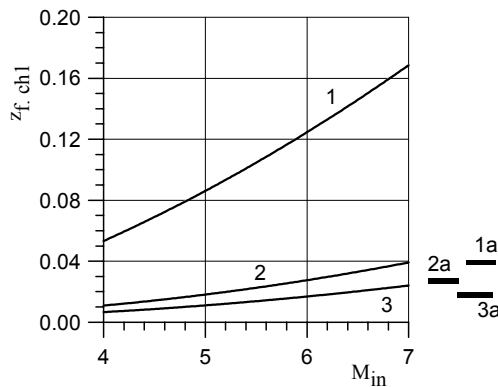


Fig. 3. Molar fractions of the fuel injected into the first plenum chamber. 1— H_2 ; 2— C_2H_2 ; 3— C_3H_8 ; curves 1a, 2a, and 3a show the lower ignition limits for H_2 , C_2H_2 , and C_3H_8 , respectively.

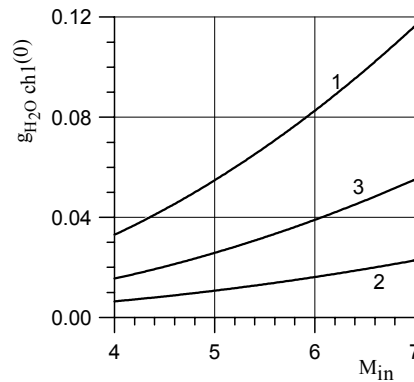


Fig. 4. Mass fractions of water in the working body. 1–3 – fuels: 1— H_2 ; 2— C_2H_2 ; 3— C_3H_8 .

may be greater than the full-scale one, then one may use a hydrocarbon fuel at lower M_{in} numbers as well.

Figure 4 shows the mass fractions of steam in the working body. The changeover from hydrogen to a hydrocarbon fuel such as acetylene or propane allows one to substantially reduce the water content. However, in this case carbon dioxide appears in the working body. Indeed, the mass fractions of CO_2 in the working body at $M_{in}=7$ amount to $\sim 11\%$ and $\sim 10\%$ for acetylene and propane, respectively. It should be noted that the mass fraction of steam in the mixture for $M_{in}=4-5$ is small, about (3-5)%. Such water contents correspond to the natural state of atmosphere at temperature $\sim 30^\circ C$ and to relative air humidity 80-100%. For this reason, modeling the working body at $M_{in}=4-5$ with invoking hydrogen combustion seems to be well justified even in problems with rather stringent requirements imposed on the composition of the working body.

Four-component mixtures. A substantial decrease in the steam and carbon dioxide content may be achieved by replacing part of the fuel with nitrogenous oxide N_2O [1]. As N_2O decomposes, nitrogen and oxygen are being released, together with 1.86 MJ/kg of heat. In the general case, the initial mixture injected into the first plenum chamber is a four-component one: fuel + nitrogenous oxide + compensating oxygen (or compensating nitrogen) + air.

The decomposition of N_2O begins at $500^\circ C$ and comes to a full end at $900^\circ C$ [4]. For this reason, the initial N_2O -containing mixture should be pre-heated to such an intermediate temperature T^{int} that to ensure subsequent complete N_2O decomposition.

The fuel/nitrogenous oxide ratio may be chosen from the following considerations.

1. The fraction of N_2O should be chosen such that, during the decomposition, the amount of formed oxygen would be sufficient both for the fuel combustion and for raising the mass fraction of oxygen in the working body to 0.231. In this case, no compensating oxygen or nitrogen should be added into the initial mixture, and the initial mixture injected into the first plenum chamber is in fact a three-component mixture: fuel + nitrogenous oxide + air. Here, one should observe that, on the complete combustion of fuel with air (or some fraction of fuel with air), the temperature would be higher than the onset temperature for N_2O decomposition.

2. The fraction of N_2O should be chosen such that the mass fractions of H_2O and CO_2 in the working body would always be lower than certain preset values determined by problem requirements. As a limiting case, the initial mixture may contain just nitrogenous oxide plus compensating nitrogen. In this case, the working body will be pure air (within an accuracy of 1% with respect to argon, which, although contained in atmospheric air, will be totally absent from the working body). In this case, however, overheating the initial mixture up to the onset temperature for N_2O decomposition at the expense of some outside, with respect to the initial mixture, source is required.

3. The fuel-nitrogenous oxide ratio may be chosen arbitrary, based on technical and economical considerations.

4. The fraction of fuel should be chosen such that, during its combustion with atmospheric oxygen, the initial-mixture temperature would run into values that ensure complete decomposition of N_2O . In the present study, it is this very case that was considered. The increase in the initial-mixture temperature from $T_{chl}=300K$ to T^{int} is only due to fuel combustion heat. As an initial temperature T^{int} , the temperature 1100K was taken. With it, we adopt the following requirements. a). Till the temperature T^{int} is reached, the rise in temperature due to the heat released during possible decomposition of some part of N_2O may be ignored. This heat will go in the reaction "stock" since, to ensure complete decomposition of N_2O , the temperature should rise continually. b). The temperature increase from 1100K to the complete decomposition temperature of N_2O , $\sim 1170K$, will be due to the N_2O decomposition heat.

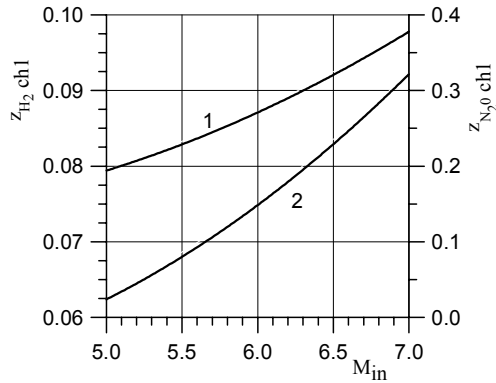


Fig. 5. Molar fractions $z_{H_2\text{ ch1}}$ and $z_{N_2O\text{ ch1}}$ of hydrogen and nitrogenous oxide injected into the first plenum chamber. 1— H_2 ; 2— N_2O .

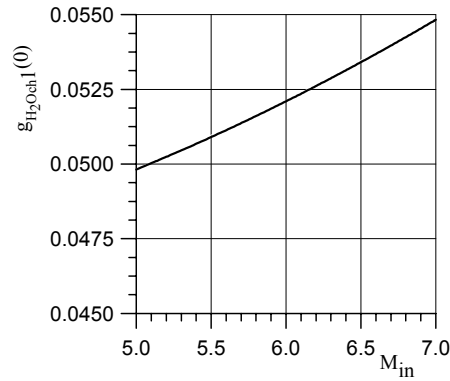


Fig. 6. Mass fractions of steam in the working body; fuel — $H_2 + N_2O$.

Since, as T^{int} , the temperature 1100K was adopted, then the M_{in} number, from which on N_2O will be used is restricted by the relation $T^{\text{int}} = T_{0\text{in}}$. For a trajectory with a velocity head 0.6 this implies that $M_{\text{in}} = 4.7$.

Figure 5 shows the molar fractions of hydrogen required for heating the initial mixture to $T^{\text{int}} = 1100\text{K}$ and the molar fractions of N_2O required for further bringing of the working body from the enthalpy $h^{\text{int}} = f(T^{\text{int}})$ to the enthalpy $h_{\text{ch1}} = h_{0\text{in}}$. The molar fractions of hydrogen are seen to exceed the lower ignition limit of 4%. Thus, the considered scheme with the heating of the initial mixture from 300K to 1100K due to hydrogen combustion is feasible judging from the forced-ignition condition. If, as a heating source, the acetylene or propane combustion heat is used, the molar fractions of these substances are ~1.8% and ~1.3%, which values are below the lean limit for forced ignition (2.5% and 2.37%, respectively). We may therefore conclude that hydrocarbon fuels in combination with N_2O for $M_{\text{in}} \leq 7$ cannot be used for the heating in view of their forced-ignition condition.

Figure 6 shows the mass fractions of steam in the working body. It is seen that substitution of some part of the fuel with nitrogenous oxide retains the steam content within ~5% if $M_{\text{in}} \geq 5$. In principle, this value of the steam mass fraction in the working body may be reduced by heating the initial mixture from 300K to T^{int} not only using hydrogen combustion, but also using additional external sources (e.g., in an external heater, or by electrical heating or adiabatic pre-compression [2]).

Regime duration. Figure 7 shows the time during which the condition of a constant pressure in the first plenum chamber is ensured (i.e., period over which the working body is being expelled from the plenum chamber by the piston) for the first plenum chamber volume $V_{\text{ch1}} = 50 \text{ dm}^3$ and for nozzle diameter $d_n = 1 \text{ m}$. These data were obtained for a three-component mixture with hydrogen used as fuel. For other fuels and for four-component mixtures the flow durations and the data of Fig.7 are identical within 2 % since the working-body properties for all substances used for the heating are close to one another. The latter is explained by the fact that, in our case, very lean mixtures were needed and that the working-body composition in all cases considered was close to that of air.

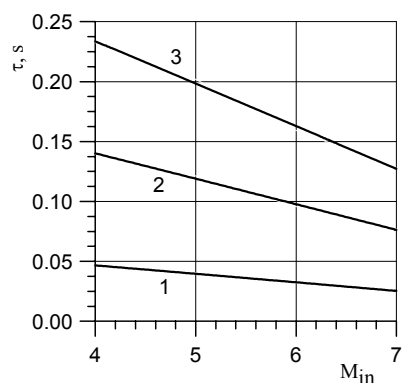


Fig. 7. Flow duration.

It is seen from Fig. 7 that, as M_{in} increases, the flow duration for $V_{ch1} = \text{const}$ and $d_n = \text{const}$ becomes shorter. The latter may be attributed to the fact that, for a trajectory with a constant velocity head, the air stagnation pressure p_{0in} increases with increasing M_{in} more rapidly than the reciprocal of the nozzle-throat area does. For this reason, as M_{in} increases, the cross-sectional area F_{1-2} of the hole between the two plenum chambers, which determines the flow duration of the facility, increases as well. The latter in turn diminishes the time of working-body ejection from the plenum chamber.

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